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Air-to-water heat pumps as a substitution of oil-boiler in a non-retrofitted multi-family building of the 70's. In-situ monitoring, actual energy balance and performance.

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Abstract

In Geneva, CO_2 emissions are mainly related to the heat supply in the residential sector, in particular in multifamily buildings (MFB). In this context, air-source heat pumps (HP) could help to reduce emissions and replace fossil-based heating systems, especially in dense existing urban areas where air is the only available renewable energy source. This study concerns the analysis of an existing non-retrofitted MF building of 1972 (4´047 m^2 heated area), whose original fossil heat supply was recently replaced by two industrial air-to-water HPs (2 x 140 = 280 kW). Based on a detailed monitoring campaign covering 15 months of operation, the main findings show that the HP system was able to cover the entire heat demand, except for a short breakdown. Thanks to optimizations in the system regulation and the choice to use only one HP in summer, the COP_{sys} increased from 1.3 in the early stage, up to 3.4 during the last summer. Based on the latter performances, we estimated that the SPF could reach an annual value of 2.3 (instead of the measured value of 1.9).

Keywords: air-to-water heat pump, multi-family building, retrofit, in-situ monitoring, energy balance, performance gap.

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1. Introduction

Nomenclature

COP_{HP}	coefficient of performance of the heat pump
COP_{sys}	coefficient of performance of system, including related auxiliary electricity
DHW	domestic hot water
E_{HP}	electricity consumption of heat pump
E_{sys}	electricity consumption of heat pump and auxiliary electricity
HP	heat pump
MFB	multifamily building
Q_{HP}	heat production of heat pump
SH	space heating
SPF	seasonal performance factor (annual or seasonal value)
ΔT_{HP}	Differential temperature between HP heat source and sink temperatures

1.1. Context and issues

In Geneva, the CO_2 emissions related to the energy sector represent 4.2 ton of emitted CO_2 per capita, of which 2.2 emitted by the heating sector, 1.1 by the transport sector (not including the airport) and 0.8 by the electricity sector [1]. Consequently, the main CO_2 emissions reduction potential lies in the heating sector, which represents about half of the final energy consumption in Geneva.

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Even though multifamily buildings (MFB) only constitute 27% of the Geneva building stock, they represent almost half of the heated floor area of the canton, namely 19.3 out of 40.9 million m^2 [2]. About half of these MFB, which were built between 1946 and 1980, are nowadays in need of retrofit and possess a strong energy saving potential. In parallel to reducing of the heat demand of the building stock, in particular by way of retrofit, reducing of the CO_2 emissions can also be achieved by replacing fossil fuels by renewable energies, in particular via heat pump (HP) systems.

However, although the market share of HPs in the Swiss residential sector grew from nearly zero in the 1990s to about 50% today, only 10% corresponds to MFB [3]. This can be explained by the fact that the implementation of HP systems in MFB is more complex than in single family buildings [4], especially because of: i) multiple households, with diluted decision power and related problems of governance; ii) buildings often located in highly dense urban areas, with limited access to renewable heat sources other than air; iii) if not threated carefully, noise emissions can easily become a barrier; iv) higher shares of domestic hot water (DHW) in overall heat demand and related high temperature, which can affect the HP performance.

1.2. éco21- HP program for multifamily buildings

Within this context, the local public utility Services Industriels de Genève (SIG) is developing a series of pilot projects concerning the replacement of fossil-based heating systems by air to water HP in MFB. These projects, which are developed under SIG's portfolio éco21, are implemented in the form of energy contracting [4].

Feasibility studies revealed the difficulties of the task: solar is not technically possible (due to complicated old roof, building being under historical heritage protection, no place available for water storage), geothermal energy and often wood and biomass are not authorized by law (due to water and air protection regulations). Air to water HPs are therefore the only solution for integrating renewable energy supply into the buildings. The challenge is important: buildings are old, there is little space, the heat distribution systems within the buildings are old, and investment costs are high [4]. Due to the age of the buildings and the restrictions to insulate the buildings envelope, the distribution temperatures are not always compatible with the ones needed for the high efficiency of the air to water HPs.

One of the major technical challenges is related to unavailability of air to water HPs specially designed for MFB. Most of the residential HPs currently have a capacity below 30 kW and are suited for single-family houses, while industrial HPs with higher capacities are not specifically designed for integration in residential buildings, specifically on noise aspects.

1.3. Objective

This paper aims to analyze one of the pilot projects of the éco21 program, in actual conditions of use. After description of the considered case study, we analyze the results of a detailed monitoring campaign covering 15 months of operation (July 2018 – Sep 2019). A particular focus is set on the diverse optimizations which had to be done so as to reach an acceptable system performance. Basing on the results obtained by way of this optimization process, we finally estimate an optimized SPF over an entire year of operation.

2. Case study

Located in Geneva and built in 1972, the MFB under consideration has a total heated surface of 4´047 m^2 (114 residents). While its envelope has not undergone any retrofit, the existing oil boiler (319 kW) was replaced by two industrial air-source heat pumps (312 kW). Each one has a heating capacity of 156 kW and COP of 3.42 (7°C evaporator and 45/40°C condenser side) as well as four scroll compressors offering four capacity stages in response to the load or source temperature [5]. Before system replacement, the climate corrected oil consumption (final energy) for production of space heating (SH) and domestic hot water (DHW) was 158 kWh/m^2 per year.

Fig. 1. Studied collective multifamily building (left) and industrial air-source heat pumps (right)

The oil boiler was kept as backup for the first years of operation but will eventually be dismantled. The distribution includes two storage tanks in parallel for DHW (500 L each) and one for SH tank (1000 L).

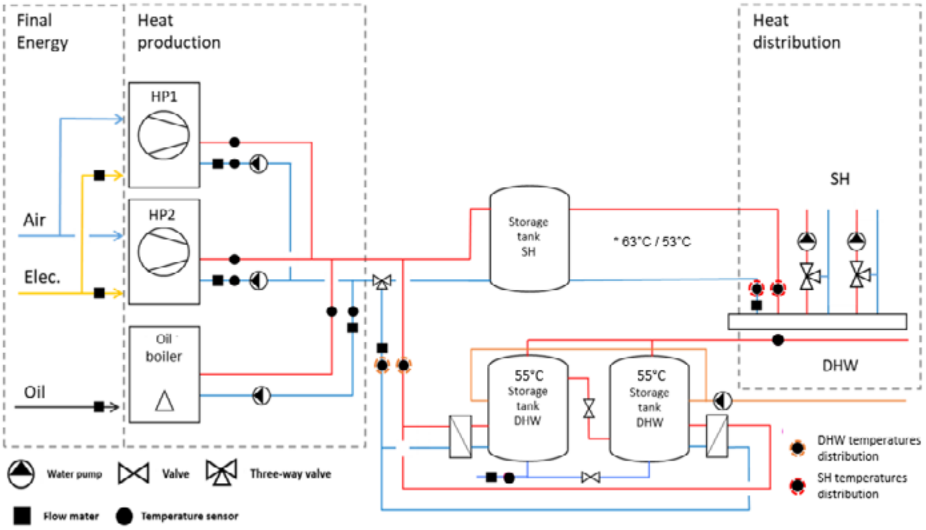

Fig. 2. Heating system (simplified diagram). * Defined at an outdoor temperature of -7°C

3. Monitoring

Instrumentation of the system is depicted in Figure 2. The monitored data are: i) electricity of each HP, including auxiliary electricity of the circulation pump on condenser side; ii) heat production of each HP; iii) heat distribution for SH (before the three-way mixing valve) and for DHW (at storage inlet); iv) DHW consumption (storage outlet).

The monitoring campaigned started in July 2018 for a period of 15 months (until December 2019). Data is acquired in 5 min time step, and aggregated in hourly and daily values.

4. Results and discussion

4.1. Building demand

The annual demand is 125 kWh/m^2 (Sep 2018 – Aug 2019), of which 47% for DHW (58 kWh/m^2) and 53% for SH (67 kWh/m^2). Latter DHW demand corresponds to the highest benchmarked values on Geneva's MFB stock [6]. On the other hand, despite the envelope not having been retrofitted, SH is well below Geneva's average for buildings from the 70's (101 kWh/m^2) and rather matches the average of the decade of 2000s [7].

The energy signature of the entire bundling shows a non-heating temperature of 17°C and SH rises to 20 W/m^2 at an outdoor temperature of 0°C (Figure 3).

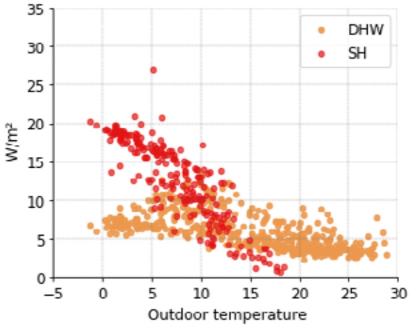

Fig. 3. Daily heat demand vs the outdoor temperature

The peak daily demand is around 25 W/m^2 (Figure 4). In daily average, DHW varies between 3 and 12 W/m^2 (summer vs winter), with an unexplained increase from February 2019 onwards.

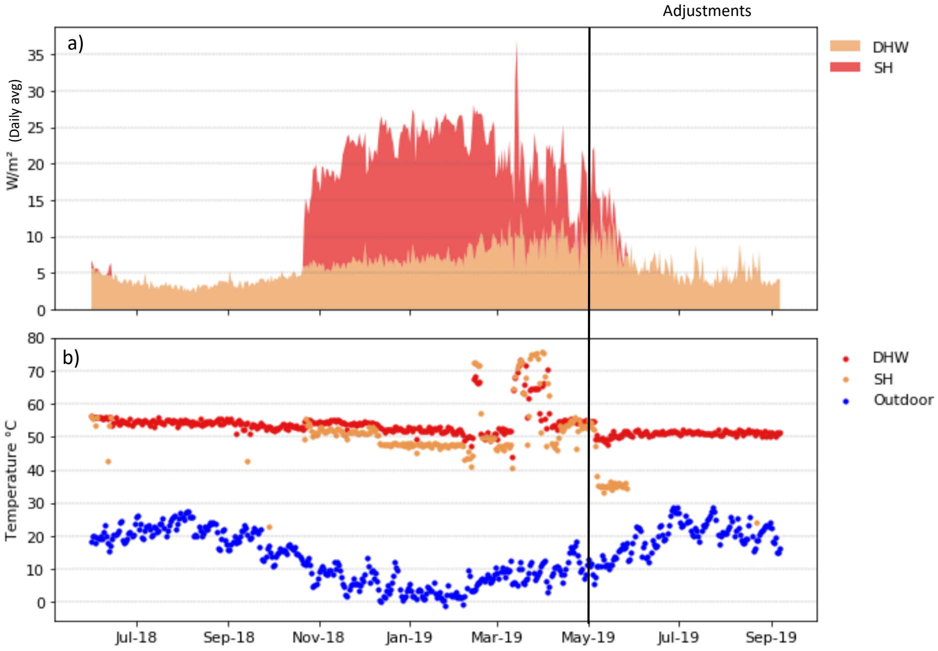

Fig. 4. Daily heat demand (a) and daily distribution temperatures (b)

Daily distribution temperatures are also depicted in Figure 4. The DHW temperature (at storage inlet) has a constant value of 50 – 55°C (except during HP breakdown in Feb and Mar 2019, see further down). Up to May 2019, the SH temperature (before the mixing valve) was relatively constant and similar to DHW. This was due to internal HP setpoints not taking into account the heating curve defined at the level of the centralized automation. This problem could finally be identified and resolved at the end of the heating season (May 2019), with a SH temperature dropping to 35°C (for an outdoor temperature above 10°C).

4.2. Heat production

The daily heat production is depicted in Figure 5. The heat production was entirely covered by both HPs, except during the HP breakdown (Feb and March 2019) when the oil boiler had to be turned on. During the first summer (up to Sep 2018), both HPs were run in parallel. From there on, priority was given to HP2 (master), with HP1 turned on for loads above approximately 15 W/m^2. During the adjustments of May 2019, priority was given to HP1, and HP2 was completely switched off for the summer period (for electricity savings on unnecessary standby mode).

Note that the HP breakdown could have been handled faster if the local technicians were used to/trained for this type of heating systems and had available spare changes, which underlines the importance of professional training.

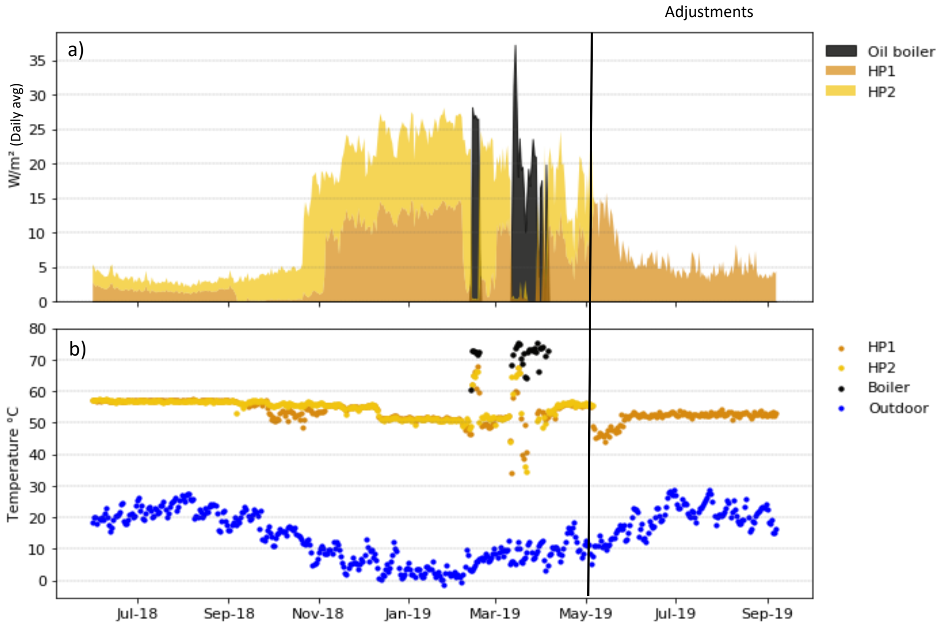

Fig. 5. Daily heat production (a) and production temperatures (b)

As pointed out before, the HP production temperature is relatively constant until the adjustments in May 2019 (Figure 5). Afterwards a short drop is observed due to the adjustments SH heating curve, followed by the DHW production during summer. During the HP breakdown, the oil boiler production temperature raised to 70°C, which is standard for this type of technology.

4.3. HP performance

For the purpose of this section, the HP performance indicators are based on the HP heat production and electricity use, and they are defined as follows:

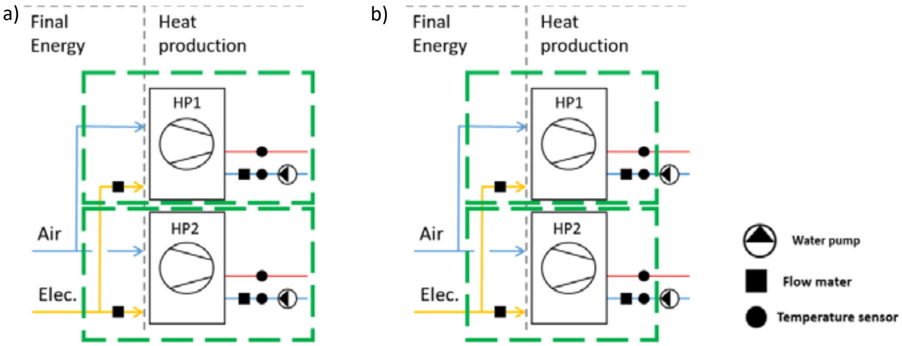

Fig. 6. Boundaries of the system performance (a) and heat pump performance (without water pump) (b)

- HP performance (Figure 6 - b) : Ratio between heat production and electric consumption of the heat pump, without auxiliary electricity consumptions, for short time periods (hourly or daily):

$$\mathrm{COP_{HP}} = \frac{\mathrm{Q_{HP}}}{\mathrm{E_{HP}}} \tag{1}$$

- HP system performance (Figure 6-a) : Ratio between heat production and electric consumption of the heat pump and its circulation pump on condenser side, for short time periods (hourly or daily):

$$COP_{sys} = \frac{Q_{HP}}{E_{sys}} \tag{2}$$

- Ratio between heat production and electricity consumption of the heat pump and the circulation pump for a given period (annual or seasonal):

$$SPF = \frac{\sum Q_{HP}}{\sum E_{sys}} \tag{3}$$

Note: As temperature sensors used to calculate Q_{HP} are close to the HP, distribution losses are included in the heat production.

4.4. System performance

The evolution of the HP system performance during the monitored period is depicted in Figure 7, along with different adjustments. Summer 2018 has the lowest $\mathrm{COP_{sys}}$, below 1.5, despite high air temperatures. This is due to a constant activation of the HP1 circulation pump (condenser side), even when the HP was off. An increase in performance is observed from Oct 2018 onwards when the constant flowrate is adjusted to follow the heat production, but $\mathrm{COP_{sys}}$ remains mostly below 2, due to constant SH temperature distribution and HP standby mode. After May 2019, the $\mathrm{COP_{sys}}$ increased significantly (2.4 - 3.4) due to the adjustment of the SH production temperature, the variable flowrate, high summer outdoor temperatures, as well as the choice to switch off the second HP during the summer period.

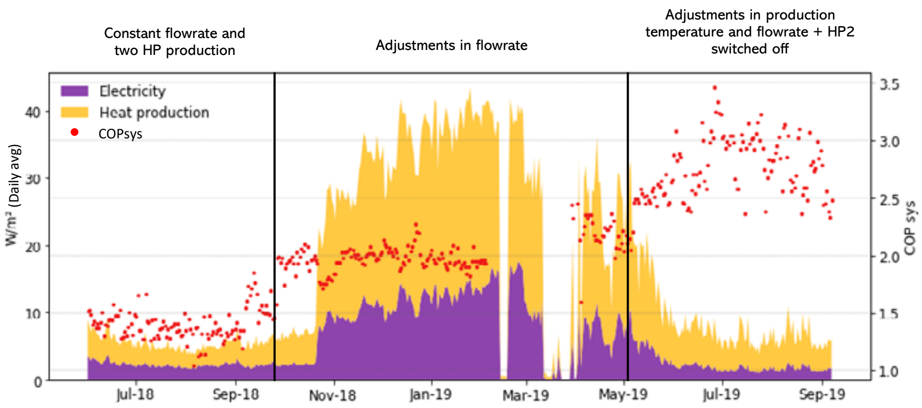

Fig. 7. Daily heat production and electricity consumption of the two HP as well as COP system performance (note: performance during the breakdown period is not considered).

The daily COP_{sys} decreases with the increase of the ΔT_{HP} as show in Figure 8. For the winter 2018-2019 and summer 2019, the COP_{sys} ranges between 3.7 to 1.8 for a ΔT_{HP} of 20 and 50 K, respectively. Note the lower performance during summer 2018 is due to the high electricity consumption induced by the constant flowrates, unrelated to temperature levels.

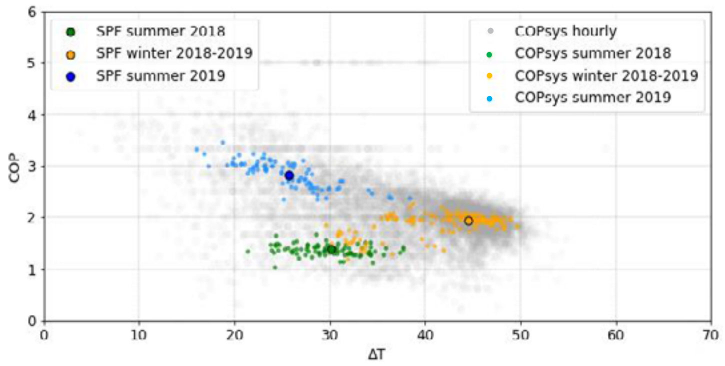

Fig. 8. COPsys and SPF as a function of ΔT_{HP}, for each season (Summer: 1st June - 31st Aug; Winter: 1st Sep - 31st Jan).

4.5. Heat pump performance

In this section, the monitored performance is compared to the one announced by the manufacturer, which is done at HP level. In the case of the manufacturer values, the COP_{HP} is given for continuous HP operation, at full power capacity (four compressors) and without auxiliary electricity consumptions. In order to approach these conditions, the hourly monitored data was filtered to identify the hours when the HP worked at least 30 minutes (note: in the case of summer 2018, the filter was reduced to 18 min, due to the higher power capacity of the two HP set-up which induced shorter durations of heat production). Furthermore, the electricity consumption of the circulation pumps (estimated to approx. 3 kW each) was deducted from the monitored electricity consumption, according to the type of flow rate of each period (constant / variable).

As a result, COP_{HP} (Figure 9) has higher values than COP_{sys} (Figure 8). In addition, the values of summer 2018 are now aligned with the ones of following periods, which highlights the fact that the poor COP_{sys} of that period was due to constant operation of the circulation pumps. Finally, a monitored COP_{HP} has the same trend as the one by the manufacture, with slightly lower values as is frequently observed difference between in situ monitored versus lab measured values [8, 9, and 10]. In conclusion, the low COP_{sys} observed was not due to a deficiency in the HP machine but to a non-optimal system operation.

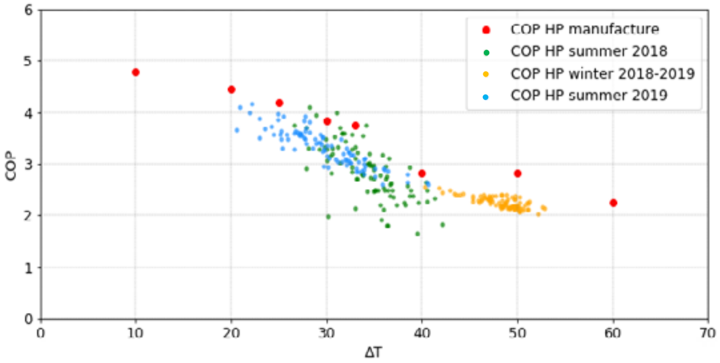

Fig. 9. Daily COP_{HP} filtered for each season and COP manufacture as a function of the ΔT_{HP}.

This analysis further suggests that HP systems should have a dedicated electrical energy meter for the HP (without auxiliary electricity), in order to verify the proper performance according to the manufacture values and help identify auxiliary electricity issues.

4.6. Optimized system performance

As observed above, the system optimizations in May 2019 lead to a clear increase of the COP_{sys} (Figure 7). Given this increase, we finally estimate an optimized SPF over an entire year of operation (Sep 2018 – Aug 2019), based on daily values, with the following hypotheses:

- The heat production is supplied by the HPs year-round (no HP breakdown).
- The daily COP_{sys} is estimated by way of the quadratic regression in Figure 10, on the optimized period, which allows to calculate the related daily electricity consumption.
- Throughout the year, as the ΔT varies between 20 and 55 K, the regression is only applied to this range. The temperature difference outside of this range are not considered.

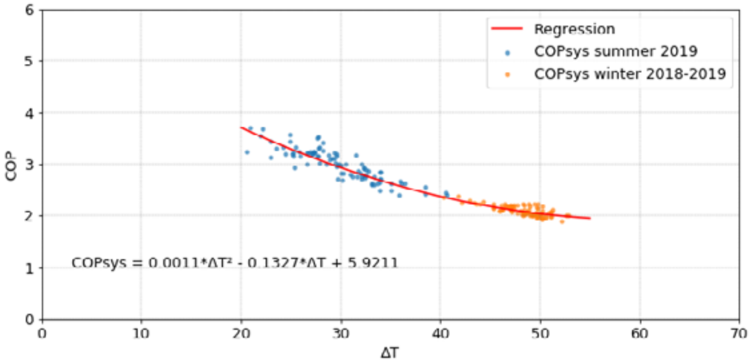

Fig. 10. Quadratic regression of the COP_{sys} as a function of the ΔT_{HP} on the optimized period (Nov 2018 - Aug 2019).

As a result, Figure 11 shows a slightly decrease of the electricity consumption (54.7 to 54.3 kWh/m^2). Note that latter still is a conservative value, because it does not include the adjustment of the SH production temperature. The total heat production increases to replace the breakdown period (HPs production year-round). It shows that a SPF of 2.3 could potentially be achieved (instead of a measured value of 1.9).

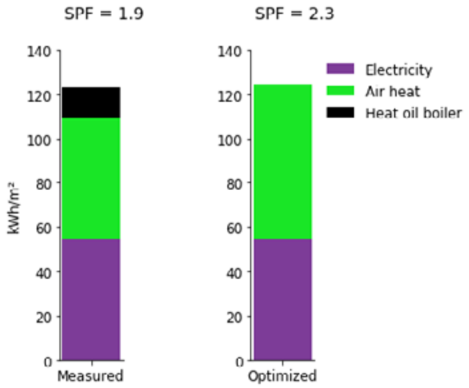

Fig. 11. Measured and optimized HP system electricity and absorbed heat (Sep 2018 – Aug 2019)

5. Conclusions

This paper focuses one a pilot project of the local public utility, concerning the replacement of fossil-based heating systems by air to water heat pumps in multifamily buildings. In the building under consideration (4´047 m^2), heat production by way of a centralized oil boiler was replaced by two industrial air-source heat pumps (2 x 156 kW = 312 kW).

A detailed monitoring campaign covering 15 months of operation (July 2018 – Sep 2019) shows that even in an existing and non-retrofitted building, a fossil boiler can be replaced by an industrial air-source HP system, without decrease of the thermal comfort for the tenants. However, based on the monitored data, improvements in the control system were implemented to improve the overall performance of the system, including:

i) Avoid constantly running of HP circulation pump in absence of production as they have a significant power consumption.
ii) Guarantee that HP set points take into account the heating curve defined at the level of the centralized automation.
iii) Turning off the second heat pump if a single HP is able to cover the entire demand, in order to improve the remaining HP's load factor.

As far as electrical consumption and related SPF is concerned, implementation of such systems however still needs adequate professional training, as well as careful commissioning. Future work will focus on exploring possible optimizations in the hydraulic and control system using numerical simulations.

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